Loran-C for European non-precision aircraft approaches

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Abstract
As Europe explores the future role of Loran-C, the question has been raised of whether Loran can form a stand-alone alternative to satellite navigation as a Basic Area Navigation system for aircraft flying under the Instrument Flight Rules. The leading alternative to GNSS in the view of many airlines is DME (Distance Measuring Equipment). But General Aviation interests are promoting Loran as both a more economical solution and a more suitable one for flight at low level. A key question within this context is whether Loran is capable of supporting non-precision approaches (NPAs)?

Given that Loran NPAs were approved in the USA many years ago, this question may appear superfluous. Nevertheless, the NPA programme there ran into difficulties, some of which are only now being addressed by the FAA. Further, we have a much more sophisticated understanding than previously of what are commonly the largest position error components, Additional Secondary Factors (ASFs). Thus, revisiting the issue is fully justified.

The paper concentrates on the accuracy of Loran-C under the special conditions of non-precision approaches to multiple runways of airports. Repeatable accuracy is also assessed under European conditions in the light of factors that include ground-wave attenuation, skywave-groundwave interference, atmospheric noise, envelope-cycle discrepancy, carrier-wave interference and the effects of weather. The results of this assessment are supported by experimental data that additionally takes weather factors into account.

Our ability to compute and measure ASFs over both smooth and irregular terrain is then considered. The special case of approaches to an airfield is particularly simple: apparently only a single ASF value per Loran station is required. But, if this is so, would this value still be valid at those distances from the airfield, and at those heights above the ground, at which aircraft join the approaches? These issues are explored using a powerful ASF computer model. Further, are those ASF values sufficiently constant in time? This question is assessed using data from North America and estimates for European conditions.

The paper concludes that the accuracies achievable are indeed sufficient to support non-precision approaches. And, as suspected, only a single ASF value per Loran station is required. Further, this single value will serve for the whole year at most European airfields. In exceptional conditions seasonal adjustments will be required and a mechanism for supporting these is described.

1 Introduction

In both the United States and Europe currently there are debates regarding the possible future role of Loran-C in aviation. Both the FAA and Eurocontrol are sponsoring studies to assess Loran performance. A key issue in these investigations is whether the accuracy of Loran is adequate to support non-precision approaches.

In recent Annual Conventions of the ILA, strong arguments have been advanced for considering Loran as part of an integrated navigation system with a global satellite navigation system (GNSS). In Europe, the Steering Committee of the Northwest European Loran System (NELS) have gone as far as to state that: “The original NELS service does not meet the requirements for a separate standalone system. The future of NELS should be as part of an integrated system” [1]. Various strategies have been considered, with strong proponents of integration favouring complete solutions in which pseudo-ranges from both systems contribute to a common navigation solution. There is little doubt that this approach would provide the highest performance for land vehicle tracking.

Aviation, however, regards this matter of integration quite differently. The expectation is that VOR and NDB will be withdrawn and Area Navigation (RNAV) will become the sole means of navigation [2]. For flight under the Instrument Flight Rules (IFR), GNSS is expected to become the system of choice. However, it is anticipated that GNSS alone will not provide the necessary level of performance. A second, independent, “reversionary” system will be required for at least the foreseeable future. The reversionary system favoured by the airlines employs multiple DME (Distance-Measuring Equipment) ranges. An alternative approach, strongly supported by the International Council of Aircraft Owners and Pilots Associations (IAOPA), is to use Loran-C. If Loran is to fulfil this role it will have to operate on its own, independently of GNSS. The question, therefore, is whether Loran can meet the operational and performance requirements for RNAV approval. Specifically, there is interest in whether it can safely be employed alone for non-precision approaches (NPAs).

Given that Loran NPAs were approved in the USA many years ago, this question may appear superfluous. During the late 1980s, following successful approach trials in New England [3], the then FAA Administrator initiated a programme to explore the integration of Loran into the US National Airspace System (NAS) [4]. This programme, the Early Implementation Project (EIP), featured technical and operational consultations with the users and sponsorship of research and test programs.

By 1989 the FAA's Associate Administrator for Regulation and Certification reported to the ILA Convention that "over a dozen NPAs" had been approved and users' comments had been "constructive and of a highly favourable nature". He stated that the 1981 Vermont test program had "erased any doubt that Loran could meet FAA requirements for Instrument Flight Rules (IFR) operations in the NAS." In support of this initiative, the FAA published an Advisory Circular (AC20-121A) on "Airworthiness approval of Loran-C navigation systems for use in the US National Airspace System (NAS) and Alaska" [5]. They introduced a Technical Standard Order (TSOC60b) on "Airborne Area Navigation Equipment using Loran-C inputs", for phases of flight that included approaches [6]. In parallel, RTCA developed test standards and minimum operational performance standards for airborne equipment (DO-194) [7]. The FAA and USCG then completed the installation of four additional mid-continent stations to support continuous Loran aviation operations.

In the early 1990s, the Early Implementation Program ran into difficulties. The problems appeared to have nothing to do with accuracy, but rather with receiver issues and the failure of the marine USCG system to meet aviation standards of continuity and integrity. The requirement of the receiver to detect errors within 10s proved the Achilles heel when it came to flight-testing. At the same time, the arrival of GPS took much of the momentum away from Loran-C development. The FAA's program to develop Loran instrument approach procedures was eventually terminated in the early 1990s and the test approaches Notammed out of service due to lack of receivers that could meet the TSO. Loran-C navigation systems however, continue to be certificated as VFR and IFR area navigation systems for en-route and terminal area use in the NAS. The availability and integrity problems that beset these earlier NPA flight trials are now being tackled vigorously by the FAA and are the subject of papers in this conference.

In Europe, in contrast, Loran-C has generally not played an important role in aviation. Loran is not part of Eurocontrol's current navigation strategy although it is permitted as a navigation aid for Basic Area Navigation (BRNAV) [8]. A recent study of the potential use of Loran-C for Eurocontrol has included accuracy as one of the key parameters. Since the US trials of the 1980s and 1990s, we have developed a much more sophisticated understanding of the factors that determine the accuracy of Loran-C fixes. These include both position bias errors, dominated by ASF effects (see below), and the random variations of position due to noise, interference, and other causes. The sources of these random errors are substantially different in Europe from in the US and are now well understood.

This paper concentrates on this question of the accuracy of Loran-C under the special conditions of non-precision approaches to multiple runways of airports.

2 Accuracy of Non-Precision Approaches

2.1 Non-Precision Approaches

In a non-precision approach, the navigation system provides guidance in the horizontal plane only. The pilot uses this to manoeuvre the aircraft onto the final approach track. Descent, in accordance with the approach procedure, is controlled using the measure of distance from the touch-down point provided by the navigation system, by reference to a pressure altimeter. The term "non-precision" indicates that no descent guidance is available from the navigation system itself.

2.2 Accuracy required for NPAs

The accuracy required for a non-precision instrument approach in the US is specified in AC 20-121A. The cross-track, and along-track, measurement errors of the airborne equipment must both be less than

+/-0.3NM (556m), at 95% probability. The FAA has further determined that, given a satisfactory cross-track position, the flight technical errors (FTE) – essentially, the pilot's contribution - can be expected to be less than +/-0.5NM (927m), two-sigma. The total cross-track error is then the total of the measurement error and FTE, combined as the root of the sum of the squares (RSS). It should be less than +/-0.6NM (1112m).

Outside the US, there is no Joint Airworthiness Authority (JAA) advisory material for operational or airworthiness approval of Loran-C. Where Loran-C coverage within European Airspace permits the use of Loran, AC 20-121A has again been adopted as the compliance basis. There is approval for certain BRNAV routes having acceptable Loran-C coverage. In this paper we will employ the AC 20-121A figures as the reference with which to compare the various errors.

2.3 Accuracy of Loran positions

The accuracy of a Loran-C position fix is dominated by two factors: ASFs and repeatability. ASF effects appear as position biases, essentially constant in time at a given location provided the same set of Loran stations are always used for the fix. The nature of ASFs will be explained in Section 3 and the magnitudes of ASF errors discussed there in detail.

Repeatable accuracy is the measure of the random variations of Loran positions around the mean position established from the true position and any uncorrected ASF components. The sources and magnitudes of repeatability errors will be the subject of Section 4.

In Section 5 we will consider whether, in the light of these bias and random errors, Loran-C can provide the accuracy required to meet the NPA specification.

3 ASFs

3.1 Loran position fixes and ASFs

Loran-C equipments determine their positions by measuring the time delays of signals received from transmitting stations (or the differences in the delays from pairs of stations). They then use the known velocity of propagation of radio waves to convert these time delays into the pseudoranges (or range-differences) of the equipment from the stations. Finally, the position is computed using this range information.

The velocity of propagation of Loran signals is a little less than the speed of light. Radio waves travelling through the earth's atmosphere are slowed down by a *primary factor*. Groundwaves that follow the earth's surface (the mode of propagation employed by Loran) are further delayed by a *secondary factor*. This secondary factor may be thought of as having two parts: the delay due to propagation over seawater, and the further delay due to any land. This latter factor is the A*dditional Secondary Factor*, or *ASF*.

Loran-C receivers first compute their pseudoranges (or range differences) by assuming that signals travel over seawater only, taking the primary factor and the secondary factor of seawater into account. Then, they correct the results using the ASFs of any land components of the paths. The process is analogous to the way in which a GPS receiver deals with delays due to the signals' travelling through the ionosphere and troposphere. But, in contrast to GPS corrections, Loran ASFs are virtually constant; they may be measured once and for all, recorded, and used by receivers.

Seawater paths, of course, have no ASFs. ASFs build up over land, slowly over good farming land with its high electrical conductivity, more rapidly over thin or poorly-conducting soil, and most rapidly of all over ice-fields, deserts, or bare mountains. Ignoring the ASFs in computing a receiver's position can result in errors of up to 3km. Employing ASFs correctly provides Loran's full repeatable accuracy.

In mountainous terrain there are additional ASFs due, essentially, to the extra distances the radio signals must travel over mountain peaks and down into valleys. In coastal areas ASF variations occur where land and sea meet. These *topographical* contributions to ASF values are also essentially constant in time.

ASFs can be measured and mapped using a survey ship, land vehicle, or aircraft. They can also be computed with a precision that depends primarily on the accuracy with which the conductivity of the ground and its topography are known. An efficient approach for mapping the ASFs across large areas, adopted by NELS, is to calculate them by computer and then make fine adjustments to the results using data measured at relatively sparse points [9].

In the case of aircraft approaches to airfields, however, ASFs mapped across the region are not required. The ASFs need only be measured at the individual airfield and their values incorporated within the data considered part of the airfield's published approaches [5,10]. In that way, errors resulting from ASF effects are, ideally, eliminated. We will now examine the degree to which that ideal can be realised.

3.2 Horizontal variation of ASFs

An ASF value measured at an airfield may be required to support approaches to various runways. Aircraft normally commence these approaches 10-20km from the airfield. Thus the spatial variations of ASF across the surrounding area should be considered to establish whether the airfield value is valid throughout the approaches. The FAA have stated that: "errors caused by the slower signal propagation over land and fresh water appear to be quite constant over distances up to several miles" [5]. Thus FAA practice in the EIP was to publish an ASF correction value for each of the two Loran time-differences employed for non-precision instrument approaches to the airfield. The Loran receiver would then extract these values automatically from a database, or the pilot would enter them manually into the equipment.

In Europe, Loran ASFs can now be calculated using a powerful computer model that takes into account both ground conductivity and topography [9]. Maps and databases of *modelled* ASFs (ie values not yet adjusted against measured values) are available for all NELS transmitters. The ASF prediction model has been used to investigate the rates of spatial variation of ASFs around an airfield. These variations are, of course, zero or negligible across the large geographical areas where the ASF values themselves are small. But in mountainous regions, such as Norway, ASF values are high. They reach more than 5µs, equivalent to a contribution of 1500m to a pseudorange. In these areas, the spatial variations of ASF are also largest.

To investigate this effect, the variations of the ASFs in the region around Oslo Gardermoen airport (ENGM) have been computed. We have studied the ASFs there from the three stations likely to contribute most to Loran fixes: Sylt (Germany), Vaerlandet (Norway) and Bø (Norway). The signals from the two Norwegian stations in particular reach Gardermoen via paths of quite exceptionally high and variable ASF. We first computed the ASF values for the centre of the airfield (in practice these values would be measured). Then, the changes of ASF between the airfield values and those at locations 10km and 20km north, south, east and west were calculated. The results are shown in Table 1.

Station	**Airfield ASF (µs)**	**ASF change (ns) – 10km from airfield**				**ASF change (ns) – 20 km from airfield**			
		N	S	E	W	N	S	E	W
Sylt	2.474	126	16	266	-439	201	-37	625	-425
Vaerlandet	4.216	107	-179	72	-133	-281	-383	188	-599
Bø	5.798	-56	96	-6	140	-327	152	250	-455

Table 1: ASF changes, 10 and 20km away from Oslo Gardermoen, with respect to values at the centre of the airfield [11]

Our analysis shows that if an aircraft starting an approach 10 km away in any of the cardinal directions were to use the airfield ASF values, the largest error that would result would be 439ns (132m pseudorange). If the approaches started at 20km range, the largest error would be 625ns (187m pseudorange). These are relatively small errors compared to the equipment errors allowed for an NPA (Section 2.2 above), even at this exceptionally-difficult airfield. The errors would, in any case, decrease progressively towards zero as the aircraft executed its approach. Also, being constant in time, they would have the effect of slightly warping the flight-path and could be partly taken into account in planning the approach.

3.3 Vertical variation of ASFs

Non-precision approaches typically start at a height some 3000ft above that of the airfield, so variation of ASF with height should also be considered. The ASF model predicts ASF values that vary with height in a complex way. The greatest discrepancy in the height range 0-3000ft is 425ns (127m pseudorange). This relatively small error is comparable with the horizontal variations and would also, of course, fall progressively to zero as the aircraft descended on the approach.

3.4 Seasonal variation of ASFs

ASF values depend on ground conductivity, a factor that varies seasonally, especially in those geographical areas where the land surface freezes and thaws. In temperate regions, such as most of Europe, Enge has estimated that seasonal ASF variations, if uncorrected, would contribute errors of only 40-70m (2-sigma) [13]. In northern Scandinavia, however, where freeze-thaw paths are frequently encountered, ASF variations are broadly similar to those in North America, where they have been studied extensively. The highest variation found in the USA by Wychorski is +/-300ns (+/-90m pseudorange) at Burlington, VT. [14].

US practice in the EIP was to measure and model these seasonal variations and publish current ASF values as part of the FAA's 56-day update cycle of aeronautical information [4,10,14,15]. Equivalent arrangements for use in Europe will be discussed in Section 5.

4 Repeatability of Loran-C fix

We will first consider (Sections 4.1-4.5) the individual factors that contribute to the repeatable accuracy (or random variations) of a Loran-C position fix: skywave propagation, atmospheric noise, carrier-wave interference, envelope-to-cycle discrepancy and weather effects. The magnitude of the repeatable accuracy, mapped across the NELS area by a coverage prediction model that takes all these factors into account, will then be given as an example in Section 4.6. In Section 4.7, the results of measurements of repeatable accuracy will be presented and compared with the predictions.

4.1 Skywave propagation

Loran-C employs groundwave signals. In making a position measurement, it is assumed that all signals have travelled over the surface of the earth. In practice, components of the transmission are also received via reflection at the ionosphere. These unwanted *skywave* components are greatest at night, when they may be much stronger than the wanted groundwave components [16].

Loran receivers separate the wanted groundwave component from unwanted skywave interference by making their time-of-arrival measurements sufficiently early in the received pulses. The skywave components, which have travelled via much longer paths, arrive after the measurement has been made and so (in principle) do not affect it. However, the ability of a receiver to separate groundwave from skywave signals in this way has limitations. Loran receivers that meet the IEC or RTCM Minimum Operational Performance Specification (MOPS) are required to cope with skywave components from 12-26dB stronger than the groundwave, and skywave delays as short as 37.5µs [17,18]. These receiver limitations have been built into the prediction model employed to determine the coverage of the NELS system [19]. The boundary of the published coverage is restricted to the area within which receivers that meet this MOPS are able successfully to reject skywave components of this magnitude and delay.

4.2 Atmospheric noise

In most areas of the world, the principal source of interference to Loran-C signals is atmospheric noise. The intensity of this noise, which is generated by world-wide atmospheric electrical activity, varies greatly with time, season and location. The signal-to-atmospheric noise ratio at the receiver is a factor that influences the magnitude of the random variations in the time-of-arrival measurements it makes, and hence the repeatability of the positions measured. The model used to estimate the fix stability of NELS incorporates the effects of the atmospheric noise levels measured by the International Telecommunication Union (ITU) across the coverage area [20]. The values employed are those not exceeded 95% of the time throughout the year.

4.3 Carrier-wave interference

In Europe, Loran-C is obliged to share its frequency band with a much larger number of other stations than in North America and other parts of the world. The interference received via groundwave and skywave paths from these many stations frequently exceeds the level of atmospheric noise. Thus interference usually has a more deleterious effect on signal-to-noise ratio and position repeatability in Europe than does atmospheric noise. Although no significant interferers have been detected in the frequency range occupied by the Loran signals themselves, 90-110kHz, transmissions on adjacent frequencies are a serious problem. Receiver designers are obliged to compromise between good skywave rejection (see Section 4.1), which requires a wide pass-band, and good interference reduction, which requires a narrow one. In practice, Loran receivers reduce the effects of carrier-wave interference principally by means of narrow-band notch filters, often realised nowadays using digital signal processing. In advanced receivers, these notches are tuned automatically to suppress those interferers that, by virtue of their strength and proximity to spectral lines of the Loran transmission, cause the greatest position errors.

The model employed to estimate the fix repeatability of NELS incorporates the effects of carrier-wave interference. It estimates, at closely-spaced geographical points across the continent, the strength of the signal received via ground-wave and skywave propagation from each of some 1000 known potentially-interfering stations. It assumes that the receiver deploys six notch filters optimally [19].

At the time these NELS coverage plots were produced, the majority of the most serious European interferers were stations of the Decca Navigator System. Their operation has recently been terminated, so the model is likely to have over-estimated the current effects of carrier-wave interference.

4.4 Envelope-to-cycle discrepancy

As a Loran signal propagates, a discrepancy develops between the time-of-arrival of its envelope and that of corresponding points on the cycles contained within it. This is due to small differences between the phase and group velocities of the signal. The degree of this *envelope-to-cycle discrepancy (ECD)* is determined principally by ground conductivity. The rates of growth of ECD are thus broadly correlated with those of ASF. The NELS model estimates ECD, and guarantees that everywhere within the published coverage its value should be less than +/-2.4µs, the limits that the MOPS requires receivers to be able to accommodate [17,18].

4.5 Weather effects

As with all radio systems, Loran velocity of propagation is affected to a small extent by variations in the temperature, pressure, and humidity of the atmosphere, factors that change most rapidly during the passage of frontal systems. These small variations are not taken into account in the Loran-C coverage prediction model. They do, however, contribute fully to the measured values presented in Section 4.7 below.

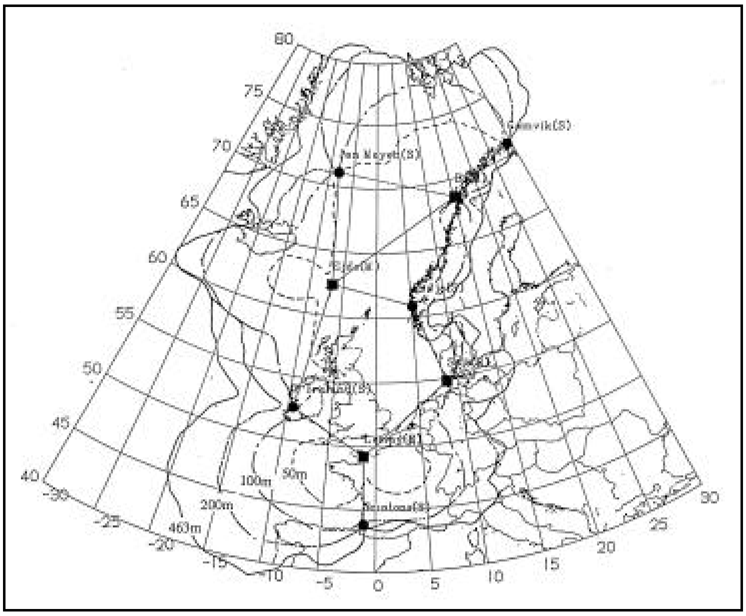

Fig. 1: Repeatable accuracy contours for system similar to NELS. The contours show the regions within which a conventional single-chain hyperbolic receiver will give a fix repeatability of 50, 100, 200 or 463m, 95% of the time. The Irish station is not yet in operation [23].

4.6 Repeatable accuracy of NELS

Fig. 1 shows the coverage of the NELS system, computed taking into account the effects of skywave propagation, atmospheric noise, carrier-wave interference and envelope-to-cycle discrepancy, as described above. It also allows for the effects of ground conductivity on the attenuation of the wanted signal components. At each point throughout a large geographical array, the signal-to-noise ratio is computed. Then, taking into account the optimal choice of stations, plus geometrical factors and the receiver’s operating mode (hyperbolic, cross-chain, or master independent), the 95%-ile repeatable accuracy is computed [19]. This repeatable accuracy is typically as good as 50m in the central regions of coverage. It falls, in a complex way, with distance from the stations. Once it has degraded to 460m, coverage is deemed to cease.

Note that there are significant areas in which the 95%-ile repeatability is 50m, or less, and even larger areas where it is 100m or less. Further, this diagram assumes a traditional receiver operating in the hyperbolic mode, employing just two time-difference measurements taken from a single chain. The extent of these areas would be increased if modern receivers, offering higher repeatable accuracies, were used. These receivers operate in the semi-circular, cross-chain, master-independent or all-in-view modes. Further, the diagram allows for strong interference from the many European Decca Navigator stations than have now been withdrawn.

4.7 Measured repeatable accuracy

Extensive data on the stability of European Loran transmissions is available from the NELS monitoring stations. Independent measurements are being carried out on a long-term basis by Beukers Technologies in the UK. Figs. 2-5 show time-difference (TD) results recorded over the three days 31 May–2 June 2001 [21]. The stations are: Sylt (Germany) at 735km range from the monitoring station; Soustons (France) at 915km; Vaerlandet (Norway) at 1109km; and Ejde (Faroe Islands) at 1193km. The time difference of each has been measured against that of the nearest station to the monitoring site: Lessay (France) at 313km. The plots include the combined effects of all the factors examined above, plus weather. The ECD factor does not affect repeatable accuracy, but the receiver does reject two additional stations it can receive, Jan Mayen (Norway) and Bø (Norway), since they fail to meet its ECD criterion.

The one-sigma values of the TD variations of the station pairs shown in these four figures are presented in Table 2 below. They have also been converted into the equivalent variations in metres of the Loran line-of-position (LOP), along the baseline joining the two stations. As would be expected, the values increase with the range of the more-distant station of the pair.

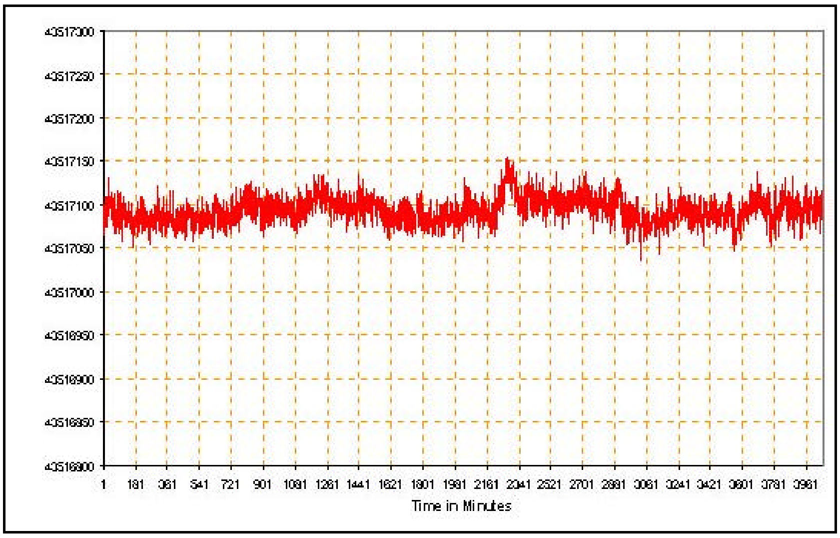

Fig. 2: Sylt-Lessay time difference variations (ns) over three days [21]

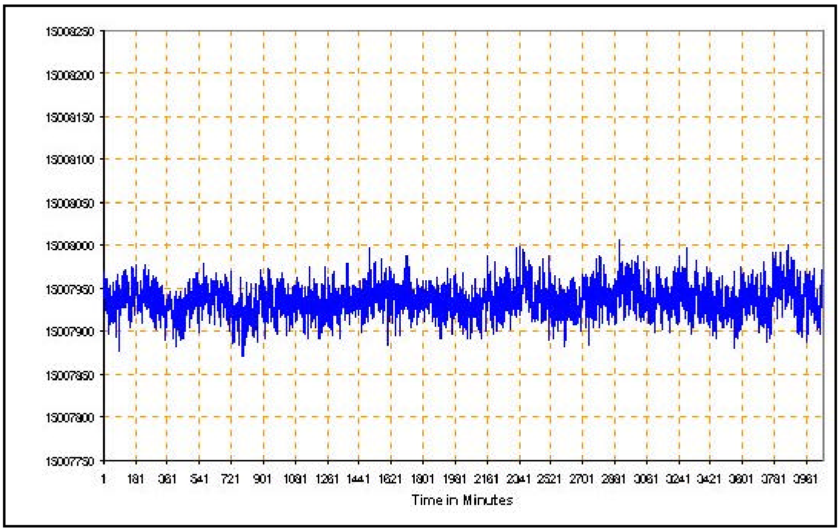

Fig. 3: Soustons-Lessay time difference variations (ns) over three days [21]

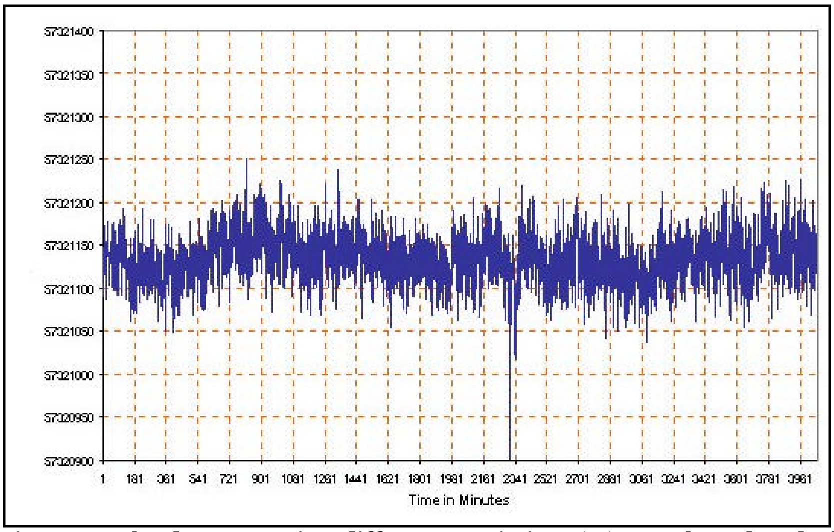

Fig. 4: Vaerlandet-Lessay time difference variations (ns) over three days [21]

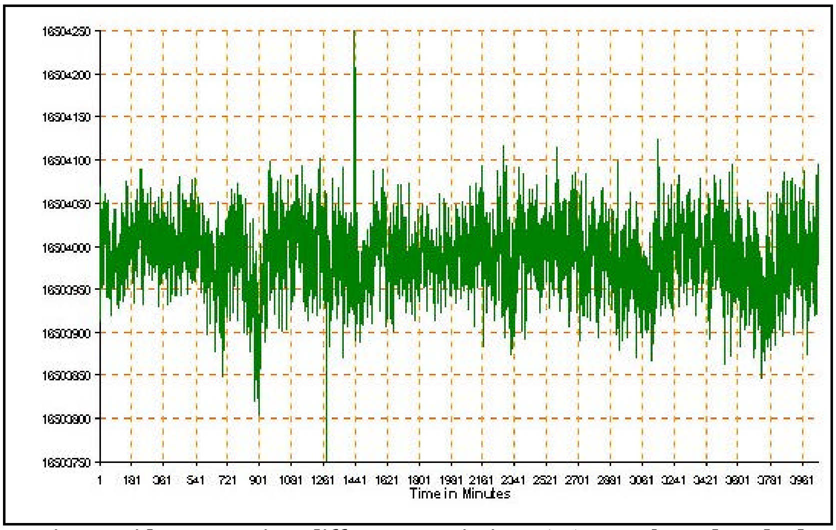

Fig. 5: Ejde-Lessay time difference variations (ns) over three days [21]

Station pair	One-sigma TD variation (ns)	Corresponding LOP variation (m)
Sylt-Lessay	14	2
Soustons-Lessay	35	5
Vaerlandet-Lessay	48	7
Ejde-Lessay	50	8

Table 2: One-sigma values of measured time-difference variations, in nanoseconds, over three days; corresponding line-of-position variation in metres [21].

The repeatability of position fixes at the monitoring station made using the Sylt-Lessay and Sylt-Ejde TDs would be approximately 13m (one-sigma) over the three-day measurement period. The measured figures in Table 2 are a little less than the values employed in computing the repeatable error contours for the NELS region shown in Fig. 1; that is, the measured performance is a little better than the predicted.

5 Accuracy of Loran-C for aviation in Europe

5.1 Non-precision approaches

In Section 3 we showed that any residual bias error resulting from uncorrected ASFs should be close to zero at the airfield itself provided that an accurate ASF measurement had been made there and updated seasonally, should that be required. The Loran equipment errors are thus likely to be dominated by the random errors due to the various effects identified in Section 4. The magnitudes of these will vary across the coverage area of the Loran system, approximately as predicted in Fig. 1. The measured values support these predictions. These 95%-ile errors are never greater than 460m, a figure that falls within the 560m specification [5].

Thus Loran-C would appear to be sufficiently accurate for non-precision approaches throughout its coverage area, provided that ASFs are measured and employed as recommended. An ASF value, 1 Byte in size, would be required for each Loran station employed for approaches at the airport. The set of ASF values would serve all NPAs to that airport. It is likely that over much of Europe it would be unnecessary to adjust these ASF values to take into account seasonal variations. However, in Scandinavia, where freeze/thaw paths are most-commonly encountered, this should certainly be considered, in accordance with practice developed in the US [4,10,14].

The source of initial ASF data would be measurements carried out at each airport when an NPA was commissioned and calibrated. The source of the updates thereafter could be monitor receivers. Tests in the US during the EIP showed that a single monitor could provide ASF seasonal updates for approaches at airfields up to 90NM distant [4,10]. It is suggested that ASF data be distributed by treating it in the same way as other aeronautical information related to the airfield approaches. It would thus be updated, if required, as part of the Aeronautical Information Regulation and Control (AIRAC) publication cycle. In that way, distribution of the data would be subject to the same checks and controls of integrity, reliability, and accuracy as other safety-critical aeronautical information. It would also be distributed by the commercial organisations (Jeppesen, Aerad, etc.) that currently handle aeronautical information in paper and electronic forms. Thus, just as most BRNAV GPS receivers are updated monthly with relevant data, so would Loran receivers; the Loran ASF values would form part of that data set.

5.2 En-route and terminal area operations

ASFs could also be employed for en-route and terminal area operations, although the need for them would be less. If ASFs are required for these modes of flight, values could be derived directly from the computer model [9]. Although not as precise as measured airfield values, the model would remove most of the up to 3km error incurred by not employing ASFs, leaving errors of less than 300ns (100m pseudorange). As the model is further refined in the future by adjustments using sparse measured values (see Section 3.2), its accuracy will improve yet further. The model can generate ASFs at spatial intervals down to less than 1km, a very much finer gradation than would be required in practice.

The size of database required for en-route and terminal area ASFs would depend on the accuracy and spatial interval chosen. For example, a set of ASFs for all usable stations, at 10x10km intervals across the coverage of NELS, would occupy approximately 3MB. However, ASF data is highly redundant (values closely resemble their neighbours) and so the database is very compressible. It has been estimated that the database could be compressed by 1-2 orders of magnitude, resulting in sizes in the range 30-300kB [22].

6 Conclusions

We have explored the question of whether the accuracy of Loran-C in its areas of European coverage is adequate to support IFR non-precision approaches. We draw on an understanding of Loran accuracy that is much more sophisticated than that available when Loran NPAs were first approved in the USA. The paper assesses the contribution of ASFs to accuracy. Using a powerful computer model it addresses the question of whether a single value taken at the airfield could be used continuously from where aircraft join approaches through to touch-down, and at all seasons of the year. The conclusion is that the spatial variations of ASFs with respect to the airfield values are small compared with the equipment errors allowed in NPAs. The seasonal variations would also be small in most areas; in those regions where they would be unacceptable, seasonal updates would be applied.

The repeatable accuracy of Loran under European conditions is then assessed in the light of factors that include ground-wave attenuation, skywave-groundwave interference, atmospheric noise, envelope-cycle discrepancy, and carrier-wave interference. The results of this assessment are supported by experimental data that also takes weather factors into account.

The paper concludes that the accuracies achievable are indeed sufficient to support non-precision approaches. Modelled ASFs would be suitable for en-route and terminal area use and are readily available.

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References

[1] Joergensen, T., 'NELS report on system integration – bringing Eurofix on air', Deutsche Gesellschaft fuer Ortung und Navigation, International Symposium on Integration of Loran-C/Eurofix and EGNOS/Galileo, Bonn, Germany, 22-23 March 2000

[2] Roper, J., Dieroff, M. and Kugler, D, 'ATS Provider Perspective on Loran-C', International symposium on integration of Loran-C/Eurofix and EGNOS/Galileo, Bonn, 22-23 March 2000.

[3] US Department of Transportation, 'Flight evaluation of Loran-C in the State of Vermont', Research and Special Programs Administration/Transportation Systems Center, , DOT-TSC-RSPA-81-10, Sep 1981.

[4] Kern, J.S., 'Impact of Loran on the National Airspace System', Proc 18th Wild Goose Association Annual Technical Symposium, Hyannis MA, 29 Oct – 1 Nov, 1989.

[5] US Department of Transportation, 'Airworthiness approval of Loran-C navigation systems for use in the US national Airspace (NAS) and Alaska', Federal Aviation Administration, Advisory Circular AC20-121A, 24 August 1988.

[6] US Department of Transportation, 'Airborne Area Navigation Equipment using LORAN-C Inputs', Federal Aviation Administration, Technical Standard Order TSO-60b, 11 May 1988.

[7] Radio Technical Commission for Aeronautics 'Minimum Operational Performance Standards for Airborne Area Navigation Equipment using LORAN-C Inputs', RTCA/DO-194, RTCA, 1986.

[8] Department of Transportation, 'Approval of U.S. Operators and Aircraft to Operate under Instrument Flight Rules (IFR) in European Airspace Designated for Basic Area Navigation (BRNAV/RNP-5)', Federal Aviation Administration, Advisory Circular 90-96, 20 March 1998.

[9] Williams, P. & Last, J.D., 'Mapping the ASFs of the Northwest European Loran-C system', Journal of the Royal Institute of Navigation, 53, 2, pp225-235, May 2000.

[10] Lilley, Robert W. & Brooks, N. Kent, 'Loran-C performance assurance for instrument approaches', Proc. 19th Wild Goose Association Annual Technical Symposium, Long Beach CA, 23-25 Oct, 1990.

[11] Williams, P. & Last, J.D., 'ASF estimates for Gardermoen, Norway', Private Communications, June 2001.
[12] Johler, J.R., Kellar, W.J. & Walters, L.C., 'Phase of the low radio frequency ground wave', National Bureau of Standards (USA), NBS Circular 573, June 1956.
[13] Enge, P.W., 'Calibration of the proposed Loran-C chain for the United Kingdom', Private Communication to Commissioners of Trinity House, Nov 1989.
[14] Wychorski, H. J., 'Construction of seasonal Loran time difference using a temperature model', Proc. Wild Goose Association Annual Technical Symposium, Williamsburg VA, 1-3 Oct, 1991.
[15] Erikson, Robert, 'What are we measuring?', Proc. Wild Goose Association Annual Technical Symposium, Williamsburg VA, 1-3 Oct, 1991.
[16] Last, J.D., Farnworth, R.G. & Searle, M.D., 'Effect of skywave interference on the coverage of Loran-C', IEE Proc.-F, 139, 4, pp306-314, Aug 1992.
[17] International Electrotechnical Commission, 'Loran-C receivers for ships', IEC-61075, Geneva, 1991.
[18] Radio Technical Commission for Marine Services, 'Minimum performance standards (MPS) – marine Loran-C receiving equipment', US Federal Communications Commission, 1977.
[19] Last, J.D., Searle, M.D. & Farnworth, R.G., 'The Northwest European Loran-C system: Coverage and performance predictions', Navigation (USA) - J. Inst. Navigation, 40, 3, pp209-226, Fall 1993.
[20] International Telecommunication Union, 'CCIR (International Radio Consultative Committee), Characteristics and Applications of Atmospheric Radio Noise Data, Report 322-3, ITU, Geneva, 1988.
[21] Beukers Technologies Inc., 'Measurements of Loran-C TD repeatabilities at Longborough, UK, 31 May-2 June 2001', Private Communication, June 2001.
[22] Williams, P. & Last, J.D., 'NELS ASF demonstration phase - Report at 10 January 1998', University of Wales, Bangor, UK, 1998.
[23] Last, J.D., Searle, M.D. & Farnworth, R.G., 'Coverage and performance predictions for the North-West European Loran-C system', Proc. Wild Goose Association Annual Technical Symposium, Birmingham, UK, 1992.

Biographies

Professor David Last holds a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He was awarded the university degrees of BSc(Eng) at Bristol, England, in 1961, a PhD at Sheffield, England, in 1966 and a DSc by the University of Wales in 1995. Prof. Last is a Board Member and holder of the Medal of Merit of the International Loran Association. He is also Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer. He has published many papers on navigation systems, including Loran-C, Decca Navigator, Argos, Omega, Marine Radiobeacons, GPS and DGPS. In Loran, he has specialised in understanding signal propagation and employing that knowledge to predict system coverage and ASFs. He has also developed receiver techniques for measuring skywave delays. He acts as a consultant on radio-navigation and communications to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

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Dr. Paul Williams was awarded the degrees of BSc(Hons) in Electronic Engineering in 1990 and PhD in 1994 by the University of Wales, Bangor. He developed his interest in radio-navigation systems during 1995/96 when he worked as a Post-Doctoral Research Fellow at Manchester Metropolitan University on a project concerning the calibration of the fixed errors of Racal's Hyperfix system. Since June 1996 he has been employed at the University of Wales on the Demonstration Phase of the "Mapping ASFs for the Northwest European Loran-C System" project. He is currently involved on a Trans European Networks project, evaluating EGNOS for maritime applications. He is a member of the Royal Institute of Navigation.

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